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Procedia Engineering 199 (2017) 2907–2912

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

A simplified method to account for the effect of human-human interaction on the pedestrian-induced vibrations of footbridges

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Abstract

For the design of slender footbridges, the vibration serviceability under pedestrian excitation is often the governing criterion. In design stage, vibration levels are predicted using simplified load models that are extrapolated from single-person force models to represent the effect of a crowd. However, these load models disregard Human-Human Interaction (HHI) and Human-Structure Interaction (HSI). This contribution investigates the effect of human-human interaction on the resulting structural response. A social force model is applied to simulate the realistic pedestrian traffic. The time-varying position and velocity of each pedestrian in the crowd are transferred into the necessary inputs for detailed step-by-step simulations of the pedestrian-induced forces and the resulting pedestrian-induced vibrations. The results show that accounting for HHI results into a reduced global walking speed. Also, the inter-person variability of the step frequencies is lower than when HHI is disregarded. As an alternative to the computationally expensive social force model, the effect of HHI is translated into an equivalent distribution of step frequencies of the pedestrians in the crowd. The results show that this simplified model allows for a very good approximation of the HHI effects on the resulting crowd-induced loading and structural response.

Keywords: Human-induced vibrations; Footbridges; Vibration serviceability; Human-Human Interaction; Social force model

1. Introduction

Vibration serviceability under human-induced excitation is often the governing criterion when designing slender footbridges. The assessment in the design stage is based on a prediction of the vibration levels and an evaluation with respect to the relevant comfort criteria [1–3]. An accurate representation of the human excitation for various loading scenarios and the footbridge's dynamic behaviour are essential for reliably predicting human-induced vibrations.

A significant amount of research has been performed so far to obtain accurate descriptions of a footbridge's dynamic behaviour by employing, for example, system identification and model updating techniques. The modelling of crowd-induced loading often extrapolates from single-person force models [1–3]. These models are derived from laboratory experiments concerning the measurement of the ground reaction forces induced by a single person on a rigid floor. In these models, neither the effects of the structural motion (Human-Structure Interaction, HSI) nor the interaction with other pedestrians (Human-Human Interaction, HHI) are considered. The presence of a crowd may significantly modify the dynamic behaviour of the coupled crowd-structure system as the result of HSI [4,5]. On the other hand, taking into

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10.1016/j.proeng.2017.09.331

Table 1. Initial and calibrated values (with percentual difference Δ) of the selected model parameters.

Parameter	λ_α [-]	Δ [%]	A^1_α [m/s^2]	Δ [%]	B^1_α [m]	Δ [%]
Initial	0.75	-	28.57	-	0.30	-
Calibrated	0.80	+6.67	9.43	-66.99	0.35	+16.67

account HHI is shown to result in a decreasing global walking speed when the pedestrian density is increased [6], in addition to an increased level of synchronization among the pedestrians for very high densities [7]. Two pedestrians are considered synchronized when they walk at the same step frequency and in phase with one another [8].

This contribution aims to characterize the effect of HHI on the resulting crowd-induced loading and structural response. Helbing's social force model for crowd dynamics [9,10] is applied to simulate uni-directional pedestrian flows. The key model parameters are calibrated to allow for realistic pedestrian flows on footbridges with pedestrian densities up to 1.5 pedestrians/m^2. Next, the effect of HHI is translated into an equivalent distribution of step frequencies. The performance of this simplified method is illustrated by comparing the resulting modal load and structural response for a crowd flow with a density of 0.8 pedestrians/m^2.

The paper is structured as follows. Section 2 introduces the social force model. Section 3 describes the simplified method introduced to account for HHI. Section 4 details the procedure for response calculation and evaluation. Section 5 discusses the effect of HHI and the simplified method performance. Finally, the conclusions are summarized in section 6.

2. Social force model

The social force model as described by Helbing et al. [9,10] is applied to simulate the pedestrian traffic on footbridges:

$$\overrightarrow{f}_\alpha(t) = \overrightarrow{f}^0_\alpha(\overrightarrow{v}_\alpha) + \sum_{\beta\neq\alpha}^{n_p} \overrightarrow{f}_{\alpha\beta}(\overrightarrow{r}_\alpha, \overrightarrow{v}_\alpha, \overrightarrow{r}_\beta, \overrightarrow{v}_\beta) + \sum_{B}^{n_B} \overrightarrow{f}_{\alpha B}(\overrightarrow{r}_\alpha) \tag{1}$$

with $\overrightarrow{v}_\alpha$ and $\overrightarrow{v}_\beta$ the velocity, and $\overrightarrow{r}_\alpha$ and $\overrightarrow{r}_\beta$ the location of pedestrian α and β at time instant t. The right hand side of Eq. (1) shows that the total social force acting on a pedestrian α is composed of three items: (1) a driving force $\overrightarrow{f}^0_\alpha$, (2) an interaction repulsive force $\overrightarrow{f}_{\alpha\beta}$ due to $n_p - 1$ neighbouring pedestrians, and (3) a repulsive force $\overrightarrow{f}_{\alpha B}$ due to the n_B borders of a walkway. The interaction force is formulated as:

$$\overrightarrow{f}_{\alpha\beta}(t) = A^1_\alpha e^{\frac{r_{\alpha\beta}-d_{\alpha\beta}}{B^1_\alpha}} \overrightarrow{n}_{\alpha\beta}\left(\lambda_\alpha + (1-\lambda_\alpha)\frac{1+\cos(\phi_{\alpha\beta})}{2}\right) \tag{2}$$

in which A^1_α is the interaction strength related to the territorial effect (= 28.57 m/s^2 [11]); B^1_α is the repulsive interaction range related to the territorial effect (= 0.3 m [11]); $r_{\alpha\beta}$ is the sum of the pedestrians' radii r_α and r_β (with $r_\alpha = r_\beta =$ 0.3 m [11]); $d_{\alpha\beta}(t)$ is the distance between the pedestrian centers of mass; $\overrightarrow{n}_{\alpha\beta}(t)$ is the normalized vector pointing from pedestrian β towards pedestrian α: $\overrightarrow{n}_{\alpha\beta}(t) = (\overrightarrow{r}_\alpha(t) - \overrightarrow{r}_\beta(t))/d_{\alpha\beta}(t)$. λ_α represents the coefficient taking into consideration the anisotropic nature of pedestrian interaction. This parameter accounts for the fact that pedestrians are far more influenced by the situation in front of them than the one behind. $\phi_{\alpha\beta}$ is the angle between the desired direction vector $\overrightarrow{e}_\alpha(t)$ and $\overrightarrow{n}_{\alpha\beta}(t)$, the vector pointing from pedestrian β to pedestrian α: $\cos\phi_{\alpha\beta}(t) = -\overrightarrow{n}_{\alpha\beta}(t)\cdot\overrightarrow{e}_\alpha(t)$.

Due to the fact that this social force model is developed to address pedestrian dynamics under panic or evacuation circumstances, significant discrepancies are observed between the simulated walking speed and the corresponding relation identified by Weidmann [6], in particular for 1.5 pedestrians/m^2 (see figure 1). Preliminary analyses show that the key model parameters influencing this speed-density relation are related to the interaction term: the parameters describing the territorial effect (A^1_α and B^1_α), and the coefficient taking into consideration the anisotropic nature of pedestrian interaction (λ_α). These model parameters are adapted such that an optimal correspondence is found with the corresponding relation identified by Weidmann [6] (see figure 1). The optimal parameter values are listed in table 1. The simulations in the following paragraphs are performed using these calibrated parameter values.

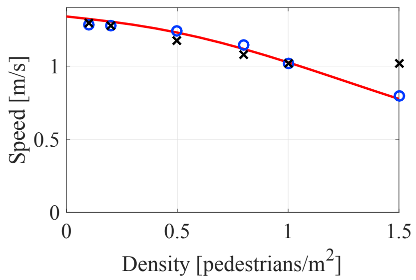

Fig. 1. Comparison between the walking speed of the simulated pedestrian flows using calibrated parameters (∘) and original parameters (×) and the fundamental speed-density relation proposed by Weidmann (line) [6].

Table 2. Comparison of the key characteristics of the three models considered to simulate the pedestrian traffic: (1) Social force model, (2) Simplified model, and (3) Unrestricted pedestrian traffic. $\mu_{f_s}(d)$ and $\sigma_{f_s}(d)$ are extracted for each pedestrian density d after following the relation between the walking speed and step frequency for each pedestrian [12]: Eq. (3)

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Crowd model	Social forces	v_s [m/s]	μ_{f_s} [Hz]	σ_{f_s} [Hz]	Trajectories
1. Social force model	yes	regulated by social forces			
2. Simplified model	no	v_{actual}	$\mu_{f_s}(d)$	$\sigma_{f_s}(d)$	straight lines
3. Unrestricted traffic	no	$\mathcal{N}(1.34, 0.26)$	1.91	0.164	straight lines

By applying the social force model described by Eq. (1), the velocity $\vec{v}_\alpha(t)$ and the trajectory $\vec{r}_\alpha(t)$ are determined for each pedestrian. The step-by-step time-variant location of each pedestrian is extracted from $\vec{r}_\alpha(t)$ according to the timing of each true step. The step-by-step time-variant walking speed of each pedestrian is extracted from $\vec{v}_\alpha(t)$ taking as the average speed during each true step. Next, the step frequency f_s of each pedestrian is determined by the following relation between the walking speed and step frequency [12]:

$$f_s = 0.35v_s^3 - 1.59v_s^2 + 2.93v_s \tag{3}$$

The trajectory, the walking speed and step frequency constitute are necessary inputs for detailed step-by-step simulations of the pedestrian-induced forces and the resulting pedestrian-induced vibrations.

3. Simplified model to account for HHI

The simulation of pedestrian flows regulated by social forces as discussed in section 2 is computationally expensive. Therefore, it is investigated if the effect of HHI on the resulting structural response can be simulated by considering an equivalent normal distribution of (constant) step frequencies for the pedestrians in the crowd: $\mathcal{N}(\mu_{f_s}, \sigma_{f_s})$. In this way, a similar approach is taken as the one introduced by the design guides Sétra [1] and HiVoSS [2] whereby a different distribution of step frequencies is defined for low pedestrian densities (<1.0 pedestrians/m^2, with $\mu_{f_s} = f_s$ and $\sigma_{f_s} = 0.175$Hz) and high pedestrian densities (≥1.0 pedestrians/m^2, with $\mu_{f_s} = f_s$ and $\sigma_{f_s} = 0$Hz), with 1.0Hz$< f_s <$ 2.5Hz. For the simplified method introduced here, the mean value and standard deviation of the step frequencies will be set to match the corresponding output of the social force model defined in section 2 (see table 2). The considered walking trajectories are assumed the same as the case that completely disregards HHI, in which the trajectories consist of straight lines parallel to the longitudinal axis x of the bridge deck. The offsets in the lateral direction are chosen randomly along the bridge deck width. All pedestrians are assumed to move at the same walking speed $v_s = v_{\text{actual}}$. The arrival times are assumed to follow a Poisson distribution [13] (see section 5.2). Thus, the simplified method translates the effect of HHI only into an equivalent distribution of step frequencies. As a reference case, also fully unrestricted pedestrian traffic is considered by assuming a normal distribution of the walking speed ($v_s \sim \mathcal{N}(1.34, 0.26)$m/s [9]) and following Eq. (3), the distribution of the step frequencies corresponds to $f_s \sim \mathcal{N}(1.91, 0.164)$Hz.

Table 2 lists the key characteristics of the three models considered here to simulate the pedestrian traffic. In the social force model, a pedestrian's walking speed and step frequency is derived from the detailed social force calculations.

The simplified model uses the key characteristics of the social force model as input, but avoids the computationally expensive social force calculations itself. This means that once the characteristics for each pedestrian density are known (an analysis which only has to be performed once), the corresponding response calculation is inexpensive.

4. Response calculation and evaluation

To compute the resulting crowd-induced loading and structural response, the simulation model as described in [14] is applied. This simulation model applies a single-step force model describing the walking load of a single pedestrian as well as a structure model describing the dynamic behavior of the footbridge. These two elements and the corresponding statistical analysis and selected time parameters are briefly discussed next.

Single-step load model

In the present study only the vertical component of the walking load is considered, as this is the only component relevant for the considered footbridge (see section 5.1). The generalised single-step load model by Li et al. [15] is applied. The single-step load model only depends on the pedestrian's weight G and the step frequency f_s whereby the latter follows as output from the considered pedestrian flow model (see section 2).

Structure model

The resulting structural response is calculated using the uncoupled governing equations of motion for a linear finite element model with proportional damping in modal coordinates:

$$\ddot{\mathbf{z}}(t) + \mathbf{\Gamma}\dot{\mathbf{z}}(t) + \mathbf{\Omega}^2\mathbf{z}(t) = \mathbf{\Phi}^{\mathsf{T}}\mathbf{P}(t) \tag{4}$$

where $\mathbf{z}(t) \in \mathbb{R}^{n_{\text{DOF}}}$ is the modal coordinate vector, $\Omega^2 \in \mathbb{R}^{n_{\text{DOF}} \times n_{\text{DOF}}}$ is a diagonal matrix containing the square of the natural frequencies ω_j in rad/s, $\Gamma \in \mathbb{R}^{n_{\text{DOF}} \times n_{\text{DOF}}}$ is a diagonal matrix containing the terms $2\xi_j\omega_j$ with ξ_j $[-]$ the modal damping ratios, $\mathbf{\Phi} \in \mathbb{R}^{n_{\text{DOF}} \times n_{\text{DOF}}}$ a matrix which has the mass-normalised mode shapes $\boldsymbol{\phi}_j$ as columns and $\mathbf{\Phi}^{\mathsf{T}}\mathbf{P}(t)$ the modal projection of the external forces $\mathbf{P}(t) \in \mathbb{R}^{n_{\text{DOF}}}$. By retaining only the relevant modes in a modal decomposition ($n_m \lll n_{\text{DOF}}$), the model order is drastically reduced by, i.e. $\mathbf{z}_r(t) \in \mathbb{R}^{n_m}$ as $\mathbf{u}(t) = \mathbf{\Phi}_r\mathbf{z}_r(t)$ and $\mathbf{\Phi}_r \in \mathbb{R}^{n_{\text{DOF}} \times n_m}$, with $\mathbf{u}(t)$ the vector of displacements.

Statistical analysis and time parameters

The time step in the response calculation is set to 0.01s. The characteristics of the resulting crowd-induced loading and structural response are derived for the stationary part of the pedestrian flow. Analysis shows that a stationary flow is obtained after $3T$, with $T = L/v_{\text{weidmann}}(d)$, where L [m] is the length of the bridge, and $v_{\text{weidmann}}(d)$ is the corresponding walking speed as specified by Weidmann [6] for a pedestrian density d. To avoid correlation between adjacent time windows in the statistical analysis, a time shift of $\Delta T = 20$ s is applied. The latter is determined for the present application such that an autocorrelation lower than 0.1 is obtained.

5. A simulation example

In this section, the impact of HHI and the performance of the simplified method introduced in section 3 is investigated by analysing the crowd-induced loading and structural response for a pedestrian density of 0.8 pedestrians/m^2.

Section 5.1 and 5.2 respectively present the considered footbridge and crowd parameters. Section 5.3 discusses the results.

5.1. Footbridge parameters

The considered footbridge has a span of 50 m and a bridge deck that is 3m wide. Only the fundamental vertical bending mode is considered with a sinusoidal mode shape and a modal mass equal to half of the total mass of the bridge as for a simply supported Bernoulli beam. The modal mass is set to 25×10^3kg. As footbridges are generally lowly-damped, a modal damping ratio of 1% is considered. The natural frequency is set to 2Hz.

5.2. Crowd parameters

The simulations are performed for a pedestrian density of 0.8 pedestrians/m^2. The present study considers unidirectional pedestrian flows. To achieve normal walking behaviour by the time a pedestrian enters the bridge, the initial positions are set to $x = -5$m and $y = [0.3, W - 0.3]$m with a 0.3m offset away from the borders in the lateral

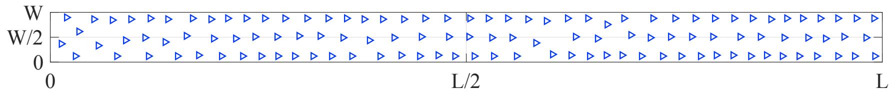

Fig. 2. The representative snapshot of pedestrian locations in a crowd flow with a density of 0.8 pedestrians/m^2.

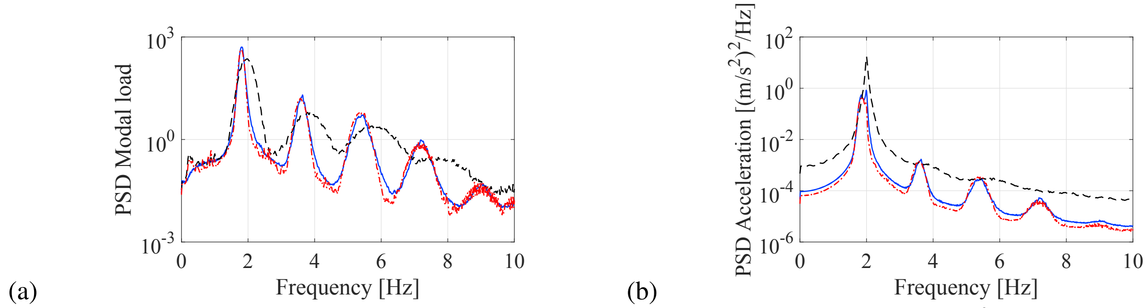

Fig. 3. The PSD of modal load (a) and acceleration (b) due to the pedestrian flow with a density of 0.8 pedestrians/m^2: solid: the social force model, dashed: the unrestricted pedestrian traffic, and dash-dotted: the simplified model.

direction in agreement with the pedestrians' radii $r_\alpha = 0.3$m (see section 2). The initial positions in lateral direction are assigned randomly, following a uniform distribution: $U(0.3, W - 0.3)$. During the initialization period when the pedestrian density is built up, the arrival times of the pedestrians are assumed to follow a Poisson distribution [13]. The corresponding arrival rate λ [persons/s] is computed from the pedestrian density d on the effective surface area A_{eff} and the estimated average time needed by the pedestrians to cross the bridge T (see section 4): $\lambda = A_{\text{eff}}\ d/T$. Once the desired pedestrian density is reached ($t = T$), the pedestrian density is kept constant through the initialization of a new pedestrian for each pedestrian that leaves the footbridge, i.e. an *off-on principle*.

When the crowd flow has stabilized (after $t = 3T$), it can be characterized by its actual walking speed v_{actual}, in this study defined as the mean value of the walking speed of all pedestrians of a stable flow (neglecting the first $3T$ of the time history).

5.3. Results

The key characteristics identified from the crowd flow regulated by social forces are as following: the actual walking speed $v_{\text{actual}} = 1.14$m/s, the mean step frequency $\mu_{f_s} = 1.81$Hz and the standard deviation $\sigma_{f_s} = 0.063$Hz. These values are lower than the corresponding values for the unrestricted pedestrian traffic (see table 2). The mean step frequency of the pedestrians in the crowd decreases as a result of the decrease in walking speed. In turn, the decrease in walking speed results from the increase in interaction force due to an increasing number of neighbouring pedestrians.

Also, the inter-person variability of the step frequencies of the pedestrian flows regulated by social forces is lower, i.e. the standard deviation of step frequencies is lower than for unrestricted pedestrian traffic. The lower inter-person variability of step frequencies is reflected in three perfect parallel lanes formed by the pedestrian flow along the bridge (figure 2). As the pedestrians' walking behaviour is constrained, the pedestrians tend to walk at the same speed, and thus, step frequency.

Figure 3(a) shows the power spectral density (PSD) of the modal load of the pedestrian flow, as simulated according to the crowd flow models as described in table 2. For all cases, a dominant peak is observed centered at the mean step frequency μ_{f_s}. Also, the contribution of the higher harmonics of the walking load can be observed as peaks centered around the integer multiples of μ_{f_s}. In addition, when the social forces are considered, the bandwidth of the peaks decreases as a result of decreased inter-person variability of the step frequencies. As a result of these changes in the distribution of step frequencies, significant discrepancies are observed between the modal load simulated for the unrestricted traffic and the one simulated for the pedestrian traffic regulated by social forces. On the other hand, figure 3(a) illustrates the excellent correspondence between the modal load simulated for the flows regulated by social forces and those simulated using the simplified method introduced in section 3.

Figure 3(b) presents the PSD of the structural acceleration response corresponding to the load cases presented in figure 3(a). For the unrestricted pedestrian traffic, the contribution of the fundamental mode clearly dominates the structural response. The latter results from the fact that the mean value of the step frequencies (1.91 Hz) is close to the corresponding natural frequency of the footbridge (2 Hz). When HHI is considered, the contribution of the fundamental mode of the structure can still be clearly identified, but is accompanied by a second peak at the mean value of the step frequencies. The latter is in this case significantly smaller than the natural frequency (e.g. $\mu_{f_s} = 1.81$ Hz < 2 Hz). As the structural response is in this case not purely characterized by resonance, as was the case for the unrestricted pedestrian traffic, now also the contribution of the higher harmonics of the walking load can be identified. Finally, figure 3 also allows to evaluate the comparison between the structural response predicted by the social force model and the one predicted by the simplified model introduced in section 3. Due to the excellent agreement in the corresponding modal load (see figure 3(a)), also a good agreement is found for the resulting structural response (see figure 3(b)).

The results demonstrate that the simplified model provides a good alternative to approximate the effect of HHI on the resulting crowd-induced loading and structural response.

6. Conclusions

A widely-applied social force model is considered to investigate the impact of HHI on the resulting crowd-induced loading and structural response. The results show that the mean value of walking speed, and thus the step frequency, of the pedestrians in the crowd is lower than the corresponding values for unrestricted pedestrian traffic. Also, a lower inter-person variability of step frequencies is found when HHI is accounted for.

The effect of HHI is translated into an equivalent distribution of step frequencies of the pedestrians in the crowd, using the distribution of step frequencies as identified from the detailed analyses that account for social forces. The performance of this simplified model is evaluated through the comparison of the resulting modal load and structural response. The above analyses show that the simplified model allows for a good approximation of the effect of HHI on the resulting crowd-induced loading.

Acknowledgements

The first author is a PhD student with the financial support from the China Scholarship Council (CSC, No.201306260117). The last author is funded by the Research Foundation Flanders (FWO). The financial support is gratefully acknowledged.

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